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THE
JOURNAL OF GEOLOGY

JANUARY-FEBRUARY, 1909

ON THE ORIGIN OF THE AMPHIBOLITES OF THE LAURENTIAN AREA OF CANADA[1]

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In a paper which appeared in the last number of this *Journal* an account was given of the development of the Grenville series in a great tract of the Laurentian Protaxis, some 4,200 square miles in extent, situated in the eastern part of the Province of Ontario, a study of which has recently been completed for the Geological Survey of Canada by Dr. A. E. Barlow and the writer.

In this tract the Grenville series is not only of great areal extent but is of enormous thickness. About one-half of this thickness consists of limestone while the remainder consists of gneisses of sedimentary origin (paragneiss), with occasional quartzites and great bodies of amphibolite. This series is invaded by enormous bathyliths of gneissic granite and while in the southeastern portion of the area toward the margin of the Protaxis, the sedimentary series is comparatively free from igneous intrusions, toward the northwest the granite in ever increasing amount arches up the sedimentary series and wells up through it, in places disintegrating it into a breccia composed of shreds and patches of the invaded rock scattered through the invading granite, until eventually connected areas of the sedimentary series disappear entirely and over hundreds of square miles the granite and granite-gneiss alone are seen, holding, however, in almost every exposure inclusions which represent the last scattered remnants of the invaded rock.

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[1] Communicated by permission of the Director of the Geological Survey of Canada.

In addition to these intrusions of Laurentian granite-gneiss, there occur in the area, also cutting the Grenville series, great intrusions of gabbro and great bodies of nepheline syenite.[1] These massive intrusions of gabbro are frequently intimately associated with and partly inclosed by bodies of amphibolite which are classed as belonging to the Grenville series. The whole forms a very complicated and, at the same time, a very interesting stratigraphical complex, as will be seen by consulting the Bancroft or Haliburton geological map sheets recently issued by the Geological Survey of Canada. The former sheet is also to be found accompanying the paper on this region which has recently appeared in the *Quarterly Journal of the Geological Society of London.*[2]

The inability to determine the origin and, therefore, the significance of the bodies of amphibolite which occur abundantly not only in this district, but everywhere throughout the Laurentian, has always proved to be one of the chief difficulties in the way of a correct interpretation of the geology of this system. The same difficulty has been met with in the case of these and allied rocks occurring elsewhere, as, for instance, the trap granulites of the Saxon Granulit Gebirge, or the amphibolites of the crystalline complex of certain portions of the Alps, the origin of which remained in doubt while the rocks with which they are associated had been definitely determined.

It is the purpose of the present paper to present briefly the results of a study of the genetic relations of the amphibolites of this particular area in the Canadian Protaxis.

The amphibolites in the area in question present a considerable variety in character and appearance but have as common characteristics a dark-gray to black color and a basic composition. Hornblende and feldspar, the latter chiefly plagioclase, are the chief constituents of the rock. Quartz, which is one of the commonest constituents in the associated gneisses, is absent or is present only in very small amount. Pyroxene or biotite often replaces the hornblende in part. The amphibolites are sometimes rather coarse, but usually medium or fine in grain, and they possess as a general rule a more or less pronounced foliated structure. They occur, as has been mentioned, associated, on the one hand, with the gabbro or diorite intrusions and as inclusions abounding throughout the granite of the bathyliths, and on the other hand they are often so intimately associated with certain developments of limestone in the form of interbedded layers that it has been found necessary to map the two rocks together and to designate them by a single color.

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[1] See Adams and Barlow, "The Nepheline and Associated Alkali Syenites of Eastern Ontario," *Transactions Royal Soc. Can.*, 1908.

[2] F. D. Adams, "The Laurentian System in Eastern Canada," *Q. J. G. S.*, 1908, p. 127.

Two of the more common varieties of these amphibolites which occur associated with the limestones were, during the course of mapping, designated as "feather amphibolite" and "granular amphibolite." The first of these always occurs in thin bands interstratified with the limestone and derives its name from the curious feather-like development displayed by the large skeleton crystals of hornblende or pyroxene which are developed in the plane of the stratification of the rock and which give to the rock a striking appearance when it is split in this direction. The granular amphibolite, which also frequently occurs as heavy bands in the limestone, is of a finely granular character, without any very distinct foliation, and on the weathered surface presents a uniformly minutely speckled appearance, owing to the intimate admixture of minute grains of hornblende and feldspar.

As the result of a very careful examination, it is possible to prove conclusively that in this area the amphibolites have originated in three entirely different ways, the resulting rocks, although of such diverse origin, often being practically identical in appearance and composition. This remarkable convergence of type, whereby rocks of widely different origin come to assume a practical identity of character, explains the difficulty which has been experienced up to the present time in arriving at a satisfactory conclusion concerning their genetic relations.

These three modes of origin are as follows:

1. By metamorphism and recrystallization of impure calcareous sediments.

2. By the alteration of basic dykes and similar igneous intrusions.

3. By the alteration of limestone through the action of the intruding bathyliths of granite.

First mode of origin.—Some of these amphibolites result from the metamorphism and recrystallization of sediments. To this class belong the "feather amphibolites" above referred to, which usually occur in thin bands alternating with crystalline limestone and evidently of like origin. They represent siliceous, argillaceous, and dolomitic laminae in the original calcareous deposit. In many cases the bands of crystalline limestone become thinner and less abundant and the composite rock gradually passes over into a body of pure "feather amphibolite." This rock can, in certain parts of the area, be traced into a comparatively unaltered variety, so that its original character is definitely determinable. Whether the "granular amphibolite," which is also found very frequently and over wide areas alternating with bands of limestone, is in some cases of similar origin, it has not been possible up to the present time to determine.

Second mode of origin.—Certain granular amphibolites represent altered igneous intrusions, for they are found in the form of dykes cutting vertically across the stratified white crystalline limestone on the shores of Jack's Lake in the township of Methuen. The limestones here dip at a low angle to the south and are excellently exposed in the form of low cliffs about the side of the lake. The typical granular amphibolite can be seen rising above the surface of the water in the form of vertical dykes, cutting directly across the stratification of the limestone. These are one to two feet wide and can frequently be seen on reaching a certain bedding plane to have been bent over in the direction of the bedding which they follow, and to have been torn apart by movements in this plane, the limestone strata having, during their upheaval, experienced somewhat extensive movements along their bedding planes. The dykes, after having followed the bedding plane for a certain distance, once more cut vertically across the latter and so reach the surface. Such dykes when seen on limited exposure of the bedded surface of the limestone, especially in contorted districts, would usually present the appearance of interstratified masses of amphibolite.

This amphibolite has the regular allotriomorphic structure of a completely recrystallized rock and differs from any of the normal igneous rocks. Under the microscope it is identical with an amphibolite described by Teall which was developed by the alteration of a diabase dyke where crossed by a line of shearing. In the case of these Canadian dykes, however, the amphibolite is not confined to that portion which has been clearly subjected to movement but forms the whole mass of the dyke. Seeing that this typical granular amphibolite can be proved to have originated from the alteration of a basic igneous dyke—in all probability originally a diabase—it is very highly probable that many other occurrences of this rock whose origin cannot be determined from their field relations may also be derived from the metamorphism of similar igneous intrusions.

Third mode of origin.—Amphibolites which are identical in physical character and in composition with those of class two are also produced by the metamorphic action exerted by the granite bathyliths on the limestones through which they cut. This is a remarkable fact and one which at first sight seems scarcely credible. It is, however, a change which has undoubtedly taken place on a large scale. The discovery that amphibolite originated in the manner just referred to explains what was a very puzzling fact in the early stages of the field-work in this region, namely, that while the granite bathyliths break through the limestone in all directions, they were filled with amphibolite masses and not with limestone inclusions. This fact was at first thought to be due to the granite happening to intrude portions of the limestone bands which were impure and thus held within themselves the material for the production of amphibolite by diagenetic rearrangment; but as occurrence after occurrence over the whole vast area was found to present the same phenomenon, it became evident that it was impossible to consider that the limestone strata had always happened to be impure at the places where the granite had broken through them, while elsewhere over great tracts the limestone contained little or no impurity. A critical study was therefore made of certain localities where the contact of the two rocks was well exposed and where the effects of the intrusion could be studied over a considerable range of country. This study showed conclusively that the limestone along its contact with the granite became impure through the development in it of bisilicates and plagioclase feldspar, and eventually when in actual contact with the intruding rock that the limestone was changed into an amphibolite.

In addition to the amphibolites originating in the three ways above mentioned, it is highly probable, judging from their character and mode of occurrence, that the great amphibolite bands associated with large gabbro and diorite masses, as for instance that running in a northeasterly and southwesterly direction through the township of Wollaston, and that occurring in the southeast portion of the township of Cardiff, thence crossing Chandos into Anstruther, represent chiefly highly altered basic volcanic ashes and lava flows connected with vents represented by the gabbro stocks. The latter of these amphibolite bands presents a great variation from place to place in the character of the constituent rock. While in some places this amphibolite is well banded, elsewhere it is streaked or presents an appearance strongly resembling flow structure, with lighter colored, lathlike forms thickly scattered through it which are highly suggestive of feldspar phenocrysts, while elsewhere again it presents an appearance suggestive of an original amygdaloidal structure. The rock, however, is so completely recrystallized that a microscopic examination does not yield any conclusive evidence concerning its original character.

That amphibolites do originate in the first manner described is clearly seen and easily understood, and that they originate in the second manner referred to is well known and has been described in many localities, but that they may originate also in the third way above mentioned is not so generally recognized, and this mode of origin therefore merits a further consideration.

DEVELOPMENT OF AMPHIBOLITE AS ONE OF THE CONTACT PHENOMENA ABOUT THE BORDERS OF THE GRANITE BATHYLITHS

About the borders of the various areas of granite, contact action is pronounced and often very striking. If the invaded rock be amphibolite, fragments torn from it are found scattered about in the gneiss, in the form of inclusions.

When the granite invades bodies of limestone, on the other hand, the phenomena resulting from the intrusion are more varied. The invading rock metamorphoses the limestone and the products of alteration may be divided into three classes:

a) The alteration of the limestone into masses of granular greenish pyroxene rock, usually containing scapolite, or into a rock consisting of a fine-grained aggregate of scales of a dark-brown mica.

b) Intense alteration of the limestone along the immediate contact into a pyroxene gneiss or an amphibolite.

c) In addition to these alteration products, in certain cases the granite dissolves or digests the invaded rock, after having altered it in one or other of the ways above mentioned.

The alteration products of Class *a* may be considered as due to the heated waters or vapors given off by the cooling magma, that is to be of pneumatolitic origin, while the alteration products of Class *b* result from the more immediate action of the molten magma itself. The products of these two classes of alteration, however, have much in common and naturally pass into one another.

The most common product of the alterations of Class *a* is a granular pale-green pyroxene rock which occurs in the limestone at or near the contact with the granite. This pyroxene rock, resulting from the alteration of the limestone, varies considerably in texture from place to place, but is usually medium in grain and granular in character, the sahlite individuals of which it is composed being short and stout with a hypidiomorphic development. Associated with the pyroxene in this rock are black mica, hornblende, scapolite, epidote, garnet, sphene, spinel, zircon, tourmaline, pyrrhotite, pyrite, molybdenite, calcite, apatite, and occasionally quartz and feldspar, as accessory constitutents. Of these minerals the mica and hornblende especially have a tendency to occur in segregations or nests composed of very large individuals, so large in fact that the mica has been mined in these pyroxene rocks at several places in the area, in one case mica crystals, having cleavage surfaces measuring two feet by two feet and a half, having been obtained. The calcite, when present in the rock, is usually in the form of very coarsely crystalline aggregates, cementing the other constituents together and into which the other minerals grow in the form of perfect crystals with excellent terminations. This calcite represents portions of the original limestone which have survived in an unaltered condition, except that they have grown more coarsely crystalline. When the calcite is subsequently removed in solution by percolating waters, spaces result which when broken into by mining are found to be lined with beautiful crystals of pyroxene or other constituents of the rock.

The other product of pneumatolitic action belonging to this class is a rock composed of an aggregate of small leaves of a very deep brown or black mica, and is less common. These mica rocks almost invariably contain more or less calcite disseminated through them, which on exposure to the weather is dissolved out, the weathered surface of the rock thus being disintegrated into a soft mass of small scales of mica. The chemical nature of this mica has not been determined, but it is probably a variety of lepidomelane, containing a considerable amount of fluorine and probably some lithia such as is found in limestones about granite intrusions in other parts of the world.

The alterations of Class *b*, whereby the limestones are converted into amphibolite, are especially well seen about the borders of the great Glamorgan bathylith whose eastern limit lies in the township of Glamorgan. This bathylith here breaks through the great body of limestone underlying the northwestern portion of the township of Monmouth and affords a most excellent and striking example of *lit-par-lit* injection. The character of this contact action can be excellently studied at Maxwell's Crossing, on Lot 15 of Range VI of the township of Glamorgan. Here the limestone, toward the granite contact, passes gradually over into amphibolite, the latter being undoubtedly produced by the alteration of the former. The invading granite in the form of apophyses wanders through the limestone series in all directions, sometimes cutting across the bedding, but very frequently in the form of narrow dykes forcing their way between the beds of the invaded limestone, changing it into amphibolite and presenting a typical instance of *lit-par-lit* injection. The granite, furthermore, not only penetrates the series, but floats off masses of the altered rock which, in the form of bands, streaks, and isolated shreds, are seen thickly scattered through the granite in the vicinity of the contact, and which, while less abundant, are found throughout practically the whole extent of this bathylith as mentioned below. The separate fragments of amphibolite where completely surrounded by the granite, while clearly nothing more than masses of altered limestone, are rather harder and more "granitized" in appearance than the amphibolite which is still interstratified with the limestone, and the fragments sometimes have somewhat flowing outlines as if they had been subjected to a certain amount of movement when in a softened condition.

When examined in thin sections under the microscope the limestone which is in the act of passing into amphibolite is seen to do so by the development in it of certain silicates. These, when the change is complete, are so abundant that they have entirely replaced the calcite while in the intervening stages some of the original calcite still remains. These silicates belong to the following species: Pyroxene, hornblende, sphene, scapolite, plagioclase, microcline, orthoclase, and quartz. The relative abundance of these minerals varies in different bands and from place to place in the rock. Their characters are as follows.

The *Pyroxene* is rather deep green in color and shows an absence of pleochroism. It is one of the chief constituents, being in the earlier stages of the change present in large amount. It first appears in individuals which are rounded in shape, do not possess crystallographic outlines or any approximation to crystalline form. In those varieties rich in calcite, the sections of the pyroxene grains are frequently nearly circular.

The *Hornblende*, which at first is much less abundant than the pyroxene, is also green in color but it is a much deeper green than the pyroxene. The grains are similar to those of the pyroxene in form, but are usually less rounded. It is intimately associated with the pyroxene, often forming adjacent grains, but there is no conclusive evidence that one mineral is derived from the other. It is strongly pleochroic.

The *Sphene* is present only in a very small amount in the form of small rounded grains of a brown color.

Scapolite is usually present in considerable amount. It polarizes in brilliant colors, is uniaxial and negative, and shows the other microscopical characters of this mineral.

The *Feldspars* vary greatly in amount. In places they form a considerable part of the rock, while no scapolite is present. In other places the scapolite seems to take their place and they are reduced to the rank of accessory constituents. All three varieties of feldspar mentioned often occur in the same specimen, their relative abundance varying from slide to slide. The polysynthetically twinned plagioclase in some cases equals the potash feldspar in amount, but usually the potash feldspars seem to be rather more abundant.

The *Quartz* is found only in a few of the thin sections and is there present only in very small amount.

When the *Calcite* survives, it can be seen that the original rock had the character of a coarsely crystalline limestone or marble. Under the action of the metamorphic processes the silicates have grown into it in the form of rounded grains which, increasing gradually in size, have finally left the calcite merely as a filling of the surviving interstitial spaces. The grains are about the same size as those of the other minerals.

An examination of thin sections of a suite of specimens of this amphibolite from a single series of exposures in the cutting on the line of the Irondale, Bancroft and Ottawa Railway at Maxwell's Crossing—some of them still containing little surviving bands of calcite and others of the harder and more altered varieties—shows that in the former pyroxene and scapolite accompany the hornblende and feldspars, while as the alteration becomes more pronounced these former minerals become less abundant and eventually disappear, giving rise to a rock composed of hornblende and feldspar, associated with which a little biotite is seen in some specimens, with certain accessory minerals which are common to both rocks. Although, as above mentioned, no actual passage of pyroxene into hornblende could be definitely observed, the hornblende individuals often have a minutely serrated edge where they come against the pyroxene, as if they were gradually enlarging themselves at the expense of the latter mineral and thus replacing it.

The amphibolite, representing the final product of the alteration, while possessing a more or less distinct foliation, has the "pflaster," "pavement," or mosaic structure characteristic of rocks which have resulted from recrystallization brought about by metamorphic processes. It presents no evidence of crushing or of having been caused to move since its recrystallization took place. This structure is quite distinct and different from that seen in the little injected bands of granite. In these, which are composed of quartz, microcline, orthoclase, and plagioclase, the quartz occurs for the most part in thin leaves with undulatory extinction and the structure of the rock is suggestive of the "mortel" or granulated structure seen in the granite gneisses.

In this remarkable occurrence, therefore, the crystalline limestone can be seen under the influence of the granite intrusion to have changed into a typical hornblende feldspar amphibolite, having passed through the intervening stage of a pyroxene scapolite hornblende feldspar amphibolite (pyroxene scapolite gneiss).

Three specimens of these amphibolitic rocks from Maxwell's Crossing, chosen to represent three steps in the progressive change from limestone to amphibolite, were selected for analysis. The analyses were made by M. F. Connor, B.Sc., of the Geölogical Survey of Canada. The figures given are in every case the mean of two determinations which agree closely with one another. The results of these analyses are as follows:

	No. 1		No. 2	No. 3
	(a)	*(b)*		
SiO_2	32.88	50.20	50.00	50.83
TiO_2	0.49	0.75	0.82	1.10
Al_2O_3	9.04	13.80	18.84	18.64
Fe_2O_3	0.77	1.18	2.57	2.84
FeO	3.48	5.31	5.51	5.97
MnO	.....	.....	0.08	0.10
CaO	30.90	17.71	10.65	7.50
MgO	4.18	6.38	4.63	4.90
K_2O	0.85	1.30	1.18	1.83
Na_2O	1.17	1.79	4.46	4.22
CO_2	15.20	.....	0.10	0.11
Cl	undet.	.....	0.10	0.03
S	undet.	.....	0.03	0.01
H_2O	1.08	1.66	1.00	1.40
	100.04	100.08	99.97	99.48

No. 1 represents the first stage of alteration and was made from a specimen which shows an alternation of narrow lighter and darker colored bands. The specimen was broken across the strike of the rock and thus included several of each of these bands, giving in this way an approximate average of the composition of the rock as a whole. Under the microscope the lighter colored bands are seen to consist of calcite, pyroxene, and a little hornblende. In the darker bands the calcite is largely replaced by the silicates, the constituent minerals of these bands being scapolite, pyroxene, some hornblende, some calcite, and a little microcline. A very small amount of sphene is also present in the rock.

The analysis as given under No. 1 *a* represents the composition of the specimen as collected; that given under No. 1 *b* represents the composition of the rock as it appears when the calcite present (determined by calculation from the amount of CO_2 present and also by direct experiment) is deducted and the amount of the remaining constituents is recalculated on the basis of 100. No. 1 *b* therefore represents the percentage composition of the silicated portion of the specimen, or, to put it in another way, it represents, except in the case of the lime, the additions made to the limestone by the granite magma in this first stage of alteration. The specimen contains 34.50 per cent. of calcite, leaving 65.50 per cent. of silicates. This silicated portion of the rock, as will be seen by comparing analysis No. 1 *b* with Nos. 2 and 3, bears a general resemblance in composition to the two latter rocks which represent the subsequent stages of alteration, the percentage of silica being practically identical in all cases.

No. 2 is the analysis of a typical specimen of the amphibolite which alternates with thin bands of the limestone at Maxwell's Crossing. It represents a second stage in the alteration, this particular specimen being practically free from calcite. Under the microscope it is seen to be composed of hornblende and pyroxene, more or less completely replacing each other in the alternate bands, together with a considerable amount of scapolite, plagioclase and untwinned feldspar. The rock also contains many minute rounded grains of sphene scattered everywhere through it, but holds no iron ore and no biotite.

No. 3 is the analysis of a harder variety, being a typical amphibolite and representing the last stage of the change. It occurs as an inclusion in the granite in the same series of exposures as that from which the other specimens were taken. The field relations show that it has been derived from variety No. 2 by further alteration. Although not differing much from No. 2 in chemical composition, under the microscope it is seen to differ considerably from it in structure, the individuals of the several constituents showing a less marked tendency to a rounded outline than in the case of No. 2. In mineralogical composition also it presents certain differences, the pyroxene and scapolite having disappeared and a certain amount of biotite having been developed.

A comparison of the analyses shows that the granite at first transfuses into the limestone, silica, alumina, oxides of iron and magnesia, with some alkalis and a small amount of titanic acid. As the alteration progresses, all these constituents continue to increase in amount. But in these later stages of the alteration the alumina, oxides of iron, and alkalis are added in relatively greater proportion than the other constituents, while no further addition of magnesia or lime takes place, the proportion of these constituents remaining essentially the same, the carbonic acid escaping and carrying the rest of the lime with it.

This means, speaking generally, that pyroxene and some scapolite were first developed in the limestone and that later the feldspathic constituents increased in amount, the calcite present being removed in solution.

A calculation of the analyses shows that Nos. 1 *b* and 2 have the following mineralogical composition:

	No. 1 *b*	No. 2
Feldspathic constituents	48.57	67.35
Pyroxenic (iron magnesia) constituents	46.63	26.28
Iron ores	3.2	5.27
	98.40	98.90
Water	1.66	1.00
	100.06	99.90

During the change of No. 1 into No. 2 and this into No. 3, the information afforded by the analyses bears out that obtained from the study of the thin sections, showing that there has been a very considerable rearrangement among the constituents of the rock. Thus it is seen that while the alumina and alkalis increase in No. 2 and No. 3, there is not a corresponding increase in the total amount of silica; the silica required to make additional feldspathic constituents being derived from some other reactions going forward in the rock.

It seems also that after the development of a certain percentage of silicates in the limestone, as shown in No. 1, during which process carbonic acid was expelled and the lime combined with it used in the production of new minerals, no further lime was fixed. In the earlier stages the waters given off by the granite having accomplished the transference of material into the limestone, passed off with the replaced CO_2 in solution, leaving the lime behind. In the later stages of the alteration, however, these waters, while continuing to deposit silicates in the limestone, made place for these latter by carrying off carbonate of lime in solution.

As will be seen, the difference in chemical composition between Specimen 2 and Specimen 3 is very small. The more highly altered rock, No. 3, is rather richer in iron, magnesia, and alkalis, while it is considerably poorer in lime and contains less chlorine. These differences are seen to represent a slight increase in the proportion of hornblende and orthoclase present and a decrease in the amount of plagioclase and scapolite in the rock.

If, for the purpose of comparing the composition of these alteration products with that of igneous rocks, the norms are calculated, these are found to be as follows. Since No. 3 is essentially the same as No. 2, the norm of the latter rock may be taken to represent both specimens and with it is given the norm of the silicated portion of No. 1 (No. 1 *b*).

	No. 2	No. 1 *b*
Orthoclase	7.23	7.74
Albite	26.20	15.24
Anorthite	27.94	25.59
Nepheline	5.56	.....
Sodalite	0.42	.....
Diopside	19.78	34.81
Akermanite	.....	6.97
Olivine	6.30	4.85
Calcite	0.20	.....
Ilmenite	1.52	1.40
Magnetite	3.71	1.80
Pyrite	0.04	.....
	98.90	98.40
Water	1.00	1.66
	99.90	100.06

In the quantitative classification the rocks, therefore, have the following position:

No. 2.		No. 1 *b*	
Class II	Dosalane	Class III	Salfemane
Order 5	Germanare	Order 5	Gallare
Rang 3	Andase	Rang 4	Auvergnase
Subrang 4	Andose	Subrang 4	Auvergnose

While, therefore, the quantitative classification is intended to apply only to igneous rocks, this final product of the metamorphism of the limestone when compared with igneous rocks readily takes its place as an andose, a group which includes many rocks which are commonly known as diorites, gabbros, basalts, diabases, and essexites.

For purposes of comparison the analysis of this amphibolite (No. 2) is here repeated together with that of an amphibolite (No. 5) produced by the alteration of a basic igneous intrusion (probably a diabase originally) and with the analyses of three typical igneous rocks which have been produced by the solidification of molten magmas.

	No. 4	No. 5	No. 6	No. 7	No. 8
SiO_2	50.00	48.81	50.86	50.73	48.85
TiO_2	0.82	0.74	....	1.59	2.47
Al_2O_3	18.84	16.62	15.72	19.99	19.38
Fe_2O_3	2.57	1.17	9.77	3.20	4.29
FeO	5.51	7.47	2.48	4.66	4.94
MnO	0.08	0.12	....	0.05	0.19
CaO	10.65	10.30	10.52	8.55	7.98
MgO	4.63	8.28	3.55	3.48	2.00
K_2O	1.18	0.76	0.90	1.89	1.91
Na_2O	4.46	3.31	3.89	4.03	5.44
CO_2	0.10	0.55	....	....	....
Cl	0.10	0.03	....	....	not det.
S	0.03	0.06	....	....	....
P_2O_5	....	....	....	0.81	1.23
H_2O	1.00	0.95	2.53	0.77	0.68
	99.97	99.17	100.22	100.13*	99.36

* Including BaO 0.27.

No. 4. Amphibolite resulting from the alteration of limestone—Maxwell's Crossing—Lot 5, Range VI, Township of Glamorgan, Ontario.

No. 5. Dyke cutting limestone—Lot 27, Range VIII, Township of Methuen, Ontario.

No. 6. Gabbro, near Baptism River, Minnesota, U. S. A. (Wadsworth, *Geol. Survey of Minn.*, 2, p. 79, 1887).

No. 7. Diorite—Big Timber Creek, Crazy Mountain, Montana (Wolff, *Bull. U. S. G. S.*, 148, p. 144, 1897).

No. 8. Normal Essexite—Mount Johnson, Quebec (Adams, *Jour. of Geol.*, April-May, 1903).

The silicated portion of the half-altered limestone (Analysis 1 *b*), which in the quantitative classification would fall under Auvergnase, has certain igneous rocks which approach it rather closely in composition, although it is higher in lime than any igneous rock whose analysis has been hitherto recorded, as emphasized by the fact that akermanite appears as a standard mineral in its norm. The following igneous rocks resemble it most closely:

	I	II	III
SiO_2	48.11	46.15	46.16
Al_2O_3	16.98	13.57	13.86
Fe_2O_3	.....	3.61	5.26
FeO	7.82	8.15	1.81
MnO	1.88	.....	.....
MgO	5.67	12.63	11.60
CaO	17.75	15.15	15.74
Na_2O	1.82	1.29	1.05
K_2O	.....	.....	0.30
H_2O	.....	.....	3.40
	100.03	100.55	99.18

I. Saussurite gabbro, Yttero, Norway.

II. Hypersthene gabbro, Urals, Russia (Loewinson-Lessing, *G. Sh. Jushno Saos*, Dorpat, 1900, p. 166).

III. Gabbro (not fresh), Laurion, Greece (R. Lepsius, *Geol. v. Attika*, Berlin, 1893, p. 98).

In connection with this alteration of limestone to amphibolite it is to be noted that the change is not one of solution or digestion of the limestone by the granite, for the fragments preserve their sharp and well-defined forms even when the alteration is complete.

The limestone, at a distance from the granite, is a white crystalline marble, containing scarcely any impurities and effervescing freely in fragments with cold dilute hydrochloric acid, showing that it is an essentially pure carbonate of lime.

The granite which brings about this alteration has not been analyzed but is in all probability of essentially the same composition as that of the adjacent Methuen bathylith, the analysis of which is given below:

SiO_2	73·33	CaO	1.66
TiO_2	0.17	MgO	0·45
Al_2O_3	13·55	K_2O	3·12
Fe_2O_3	0.58	Na_2O	5·01
FeO	1·53	H_2O	0·45
MnO	0.04		99·89

The changes are the result of the transfusion into the limestone of certain constituents which are present in the granite magma. A remarkable fact in connection with the alteration, is that the granite, which is an acid variety of the rock containing a very small amount of biotite as its only bi-silicate, where the limestone was bathed by it or actually immersed in it as in the case of the included fragments, has notwithstanding this fact transfused into the limestone not only silica, alumina, and alkalis, as might be expected, but also large amounts of magnesia and iron. The limestone evidently fixed certain constituents of the granite magma in relatively greater abundance than others, exerting a species of selective action. Many cases have been described in which a granite magma has passed by differentiation into a gabbro, but here the granite retains its normal character and at the same time changes the limestone into a rock having the composition of a gabbro.

That similar changes are brought about by the action of acid magmas upon limestones elsewhere is shown by two occurrences described by Kemp[1] and one by Lindgren. The first is from San José, in the State of Tamaulipas, Mexico, the second from Morenci, Arizona, and the third from White Knob, Idaho. In all cases highly acid intrusive rocks, quartz-porphyries or quartz-diorite-porphyries, very low in iron, penetrate limestones which are so pure that they can yield little or no garnet of themselves. In each case the intrusives have developed in the limestones large amounts not only of an alumina garnet (grossularite), but also of an iron garnet (andradite), showing that the acid magma has transfused into the limestones large amounts of SiO_2, Al_2O_3, and Fe_2O_3, which the limestones have fixed in the form of garnet.

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[1] J. F. Kemp, "Ore Deposits at the Contacts of Intrusive Rocks and Limestones and Their Significance as Regards the General Formation of Veins," *Economic Geology*, Vol. II, No. 1, 1907, p. 1, and *Trans. Am. Inst. Mining Eng.*, XXXVI, p. 192. W. Lindgren, *U. S. Geological Survey*, Professional Paper No. 43, p. 134. See also O. E. Le Roy, "The Marble Bay Copper District," *Jour. Can. Min. Inst.*, 1907, p. 248.

Kemp's conclusions concerning these occurrences exactly coincide with those reached from a study of the occurrences in the Haliburton-Bancroft area, as shown by the following quotations from the paper referred to above:

> First of all the question may be raised as to whether the eruptive has melted into its substance sufficient limestone to yield the zones which have then crystallized out from fusion. This view is opposed both by the sharp contacts afforded by the eruptive against the garnet zones; by the variability of the zones in mineralogy, and by the fact that the necessary ingredient of andradite would not thereby be afforded. In almost all cases the eruptive is a highly acidic rock, a quartz-porphyry, or quartz-diorite-porphyry. The percentage in iron is very small, far below the requirements of the iron-lime garnet, and the general composition not at all adapted to yield the zones. On the contrary we are irresistibly led to the conclusion that from the intrusive rock has come either highly heated water gas or highly heated water itself in the closing stages, and that one or both of these have brought to the limestone the silica, iron oxide, and alumina for the production of the lime-silicates. After the production of the garnet and its associates was well under way, they brought in also the copper and iron sulphides which are the commonest ores.
>
> The silica and the other dissolved materials did not wander farther from the eruptive because the limestone promptly intercepted them and locked them up in silicates; but undoubtedly carbonated water and carbon dioxide gas were yielded in great quantity, an inference which falls harmoniously in line with what we know of volcanic emissions.